Extraction of the velocity of walking human's body segments using ultrasonic Doppler

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Abstract: The focus of this paper is to experimentally extract the Doppler signatures of a walking human's individual body segments using an ultrasonic Doppler system (UDS) operating at 40 kHz. In a human's walk, the major contribution to Doppler velocities and acoustic scattering is from the foot, lower leg, thigh (upper leg) and torso. The Doppler signature of these human body segments are extracted experimentally. The measurements were made by illuminating one of these body segments at a time and blocking the remaining body segments using acoustic screens. The results obtained in our experiment were verified with the results published by Bradley using a physics-based model for Doppler sonar spectrograms.

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1. Introduction

Walking people generate Doppler signatures[1–3] that can be used for human detection and recognition. These Doppler signatures utilize oscillation of human body segments due to the walking motion and are obtained by transmitted/reflected ultrasonic or electromagnetic waves from the human body.

Doppler signatures of walking people were investigated and the results have been presented in a number of publications.[1,4] A method for estimating walking human parameters from radar measurements exploiting the Doppler signature from different human body segments is described in Ref. 3. A continuous wave (CW) radar[2] has been used for the detection and classification of people based on the Doppler signatures they produce when walking. Similar to the radar, acoustic Doppler sensors are also used to extract Doppler signatures of walking people to characterize their gait.[1]

Model-based approaches are also proposed to extract Doppler signatures of walking humans. A high resolution model of a walking human was developed to analyze continuous wave (CW) radar Doppler signatures.[2] These Doppler signatures were then incorporated in the identification of different body segments of a walking human, and it was found that, among different body segments of a walking human, the major contributors are: the feet, lower legs, thighs or upper legs, and the torso. The most widely-used biomechanical model is presented by Boulic *et al.*[5] Boulic-Thallmann's (BT) model was originally developed to provide a computationally-efficient tool for aiding computer animation. The BT model is a kinematic model with only three input parameters: the cycle length, cycle frequency and cycle phase that describe all of the dynamics. The BT model has been found to be useful in explaining the features seen in Doppler radar[6] and Doppler sonar[7] measurements of walking humans. A

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14. ABSTRACT
The focus of this paper is to experimentally extract the Doppler signatures of a walking human?s individual body segments using an ultrasonic Doppler system (UDS) operating at 40 kHz. In a human?s walk, the major contribution to Doppler velocities and acoustic scattering is from the foot, lower leg, thigh (upper leg) and torso. The Doppler signature of these human body segments are extracted experimentally. The measurements were made by illuminating one of these body segments at a time and blocking the remaining body segments using acoustic screens. The results obtained in our experiment were verified with the results published by Bradley using a physics-based model for Doppler sonar spectrograms.

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feature-based approach is presented in Ref. 6 that estimates the global Boulic parameters and also extracts the independent human motion repetition frequency based on velocity slices in the spectrogram. In Bradley's method,[7] body segments are modeled as ellipsoids and scattering is assumed to occur from different body segments such as feet, lower legs, thighs, and torso. This physics-based model was then used to predict the temporal and velocity structure observed in micro-Doppler sonar spectrograms. All the above-mentioned methods extract signals from different body segments using model-based or feature-based approaches, but so far no one has experimentally extracted the Doppler signature for individual human body segments.

This letter reports the experimental results of detecting and discriminating human motion from different human body segments with help of a CW ultrasonic Doppler sonar system.[1] The data was collected by illuminating an individual body segment such as a foot and isolating the remaining human body segments using acoustic screens. The acoustic screen not only blocked illumination of the undesired body segments, but also stopped the reflected signals from these segments to the receiving transducer. The received signal from the target of interest was then converted to baseband in-phase (I) and quadrature (Q) samples and a complex spectrogram was generated to compute the velocity of different body segments individually.

This letter is organized as follows: the principle of operation is presented in Sec. 1. Section 3 describes the experimental set up. Results are presented with discussion in Sec. 4. This letter is concluded in Sec. 5.

2. Principle of operation

The principle of UDS relies on the detection of a Doppler shift in the frequency of acoustic waves scattered by a moving target, from which a time-resolved measurement of the target velocity is obtained.[4] A continuous ultrasound signal is transmitted toward a moving target, and the received signal from the vibrating surface is FM as a result of the Doppler effect. The reflected FM ultrasound signal is received by the transducer that is co-located with the transmitter and can be mathematically expressed as

$$g(t) = A\cos(2\pi f_c t + \phi(t)), \tag{1}$$

where A = amplitude of the received signal, f_c = carrier frequency, and $\phi(t)$ = instantaneous phase and can be written in terms of scattered velocity $v(t)$

$$\phi(t) = \frac{4\pi}{\lambda}\int_{-\infty}^{t} v(t)d\tau + \phi_0,$$

2.1 Generation of I (t) and Q (t) samples

In order to demodulate the received FM signal, the FM signal is converted into baseband $I(t)$ and $Q(t)$ by multiplying the FM signal with both the carrier signal and $\pi/2$ shifted version of the carrier signal[8] as shown in the following:

$$g(t) \times g_c = \tfrac{1}{2}[\cos(4\pi f_c t + \phi) + \cos(\phi)], \tag{2}$$

where $g_c(t) = B\cos(2\pi f_c t)$ and is synthetically generated. $Q(t)$ samples can be obtained by using the following expression:

$$g(t) \times g_{co} = \tfrac{1}{2}[\sin(4\pi f_c t + \phi) + \sin(\phi)], \tag{3}$$

where $g_{co}(t) = B\cos(2\pi f_c t - \pi/2) = B\sin(2\pi f_c t)$. After performing low pass filtering on Eqs. (2) and (3), we get

$$I(t) = \cos(\phi), \tag{4}$$

$$Q(t) = \sin(\phi). \tag{5}$$

The Doppler baseband $I(t)$ and $Q(t)$ component can be decimated before combined to form a complex Doppler signal as in the following:

$$S(t) = I_{dec}(t) + iQ_{dec}(t), \tag{6}$$

where I_{dec} and Q_{dec} are the decimated I and Q samples and i is the imaginary unit.

2.2 Velocity calculation

The velocity of human body segments can be computed using a well-known spectrogram, essentially the square of the short-time Fourier transform (STFT), which can be expressed as

$$\mathrm{STFT(t,f)} = \int \mathrm{S}(\mathrm{t}+\tau)\mathrm{w}(\tau)\exp(-\,\mathrm{j}2\pi\mathrm{f}\tau)\mathrm{d}\tau, \tag{7}$$

where $S(t)$ is the complex down-converted signal as given in Eq. (6), $w(t)$ is a sliding window function (e.g., a Hamming window), t is time, and f is frequency.

3. Experimental setup

A UDS[1] was designed using two ultrasonic ceramic sensors. An HP 3314A signal generator applied a 3 V, continuous-wave electrical signal at 40 kHz to the transmitter. The received signal was recorded using a 24-bit data acquisition system (DAQ) (Echo Indigo IO) and a laptop computer with the software (Spectra Laboratory). The measurements of the ultrasonic signals from a person walking on a treadmill in a laboratory environment were conducted using the UDS. The speed of the treadmill was set and measured to be 1.34 m/s. The UDS was placed on a tripod at variable heights depending upon which part of human body was to be illuminated. The UDS on the tripod was placed close to and aligned with the intended target (left foot, left lower leg, left thigh, or the chest) to capture the maximum reflected signal from that target. We were interested in isolating different human body segments acoustically and then capturing the reflected signal from each of these segments. This was done using two acoustic screens made of cardboard. The height of the bigger screen was greater or equal to the height of the walker on the treadmill. These screens were placed between the transducers and the walker, and were perpendicular to the transmitted acoustic waves and parallel to the face of transducers. Apertures were made in the bigger screen by cutting openings at different heights corresponding to walker's foot, lower leg, and thigh heights. The dimensions (height $\times$ width) of these apertures for the foot, lower leg and the thigh were $0.077\times 0.14\ \mathrm{m}^2$, $0.33\times 0.14\ \mathrm{m}^2$, and $0.38\times 0.14\ \mathrm{m}^2$, respectively.

First, data was taken for the left foot of a walking person on a treadmill. The aperture in the screen for the left foot was left opened and all the other apertures in the cardboard were closed. The transmitted acoustic wave passed through the aperture and struck the left foot and a part of the right foot. The reflection from the right foot was blocked by the smaller screen and only the reflection from the left foot could pass through the aperture in the bigger screen back to the co-located receiving transducer. The captured signal from the left foot was then digitized for further analysis.

4. Discussion and results

A UDS is capable of resolving motions of objects whose dimensions are equal to or larger than the wavelength of the acoustic waves. Given a sampling frequency of 4.8 kHz (after decimation) and a window size of 256 samples, the frequency resolution was 18.75 Hz, corresponding to a velocity resolution of 0.081 m/s when 40 kHz transducers were used. A window size of 256 samples was found to be optimal for a sampling frequency of 4.8 kHz. This sampling frequency was obtained after performing the decimation by a factor of 20 on data that was originally sampled at 96 kHz.

The results presented in this letter were semi quantitatively compared with the results calculated by Bradley.[7] However, there is a difference between our approach and the assump-

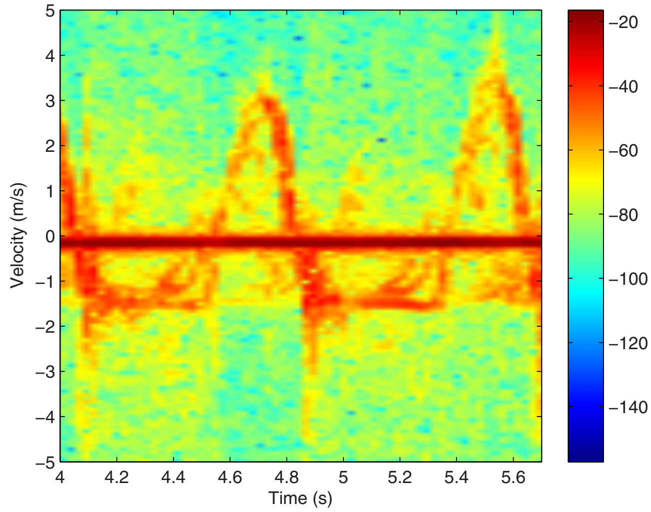

Fig. 1. (Color online) Foot spectrogram of a walking human on the treadmill.

tions made in Bradley's method. We extracted different body segments' velocities from a person walking on a treadmill, focusing the UDS such that it was perfectly aligned to the center of the intended target, making an angle of 0°. Bradley computes body segments' velocities assuming that a person is walking on the ground and receiver is placed 20 m from a 1 m high target thus making an angle of 2.86°. Bradley's method considers the bulk velocity, which is the average velocity of the walking human in addition to the segments' velocities. In our method, either there was no bulk velocity or it was negligible since the walker was on the treadmill and not on the ground. In Bradley's method, the average velocity of a walking person is assumed 1.34 m/s. Hence the velocity calculations made in Bradley method are 1.34 m/s more than the velocity values extracted in our experiment. The results presented here are from segments of the left leg (foot, lower leg, and thigh) and the torso (chest) of a walking human. For conciseness, the prefix 'left' is omitted from different body segments in the discussion to follow.

First, data was obtained by illuminating the foot of a person walking on the treadmill at 1.34 m/s toward UDS and its spectrogram is shown in Fig. 1. The spectrogram is plotted from 4.00–5.70 second (s). Heel strike of the foot on the treadmill occurred at 4.10 s and, at 4.15 s, the foot (toe-down) was on the treadmill belt. The foot stayed on the treadmill from 4.10 to 4.50 s and then took off and swung toward the sensors. In Fig. 1, during the foot contact with the treadmill belt, a backward foot drag was observed. The Doppler velocity for the foot drag was from −1.65 to −1.15 m/s. The mean velocity of the foot drag was approximately equal to the treadmill speed. At 4.50 s the foot swung toward the UDS and produced a wide range of velocities seen between 4.6 and about 4.8 s and also showed a sudden rise in velocity. The velocity width of the spectrogram is due to the reflected signal from the proximal and distal segments of the foot. In Fig. 1, the area between these two ends is filled in and represents the Doppler velocity bandwidth. The range of velocities from the distal end to the proximal end of a body segment and the point scatters between these two ends is called the Doppler velocity bandwidth. It is variable at different times depending upon which part of the foot was exposed to the UDS. At the beginning of the foot swing at 4.35 s there was a wide Doppler velocity bandwidth that became narrow at 4.60 s and widened again at 4.65 s. However, during the remaining phase of the swing, we saw a constant Doppler velocity bandwidth until the foot hit the treadmill belt at 4.9 s. At 4.85 s, the apparent increase in Doppler velocity bandwidth was because of diffraction from screens and scattering from the right foot. The returns associated with these effects observed in Fig. 1 are unimportant because they are very weak compared to the reflected signal

from the swinging left foot. The acoustic scattering from the right foot is also seen in the spectrogram at 4.25 s with Doppler velocity of 0.88 m/s and at 5.05 s with Doppler velocity of 0.86 m/s.

However, during most of the time of this measurement, the scattering from right foot was blocked with a screen and had a little effect on the spectrogram. The maximum velocity observed during the first foot swing at the distal end was 3.50 m/s at 4.75 s. At the same time, the maximum velocity for the proximal end was 2.60 m/s. However, the foot velocities at 5.54 s in the second foot swing at the distal end and at the proximal end were 4.20 and 3.40 m/s, respectively. It is this range in the velocity that we call the Doppler velocity bandwidth. It can also be observed that the slopes in the rising and falling of the foot swing were asymmetrical. The slope for the rising part of the foot swing computed from 4.37 to 4.72 s was 12.38 $\mathrm{m/s^2}$. On the other hand the slope computed for the falling part of the foot swing from 4.77 to 4.93 s was $-27.63\ \mathrm{m/s^2}$, and is 2.23 times steeper than the rising slope. The amplitude of the foot velocity was about −30 dB (re 1 V), which corresponded to the strength of the acoustic returns.

These temporal observations were compared with that predicted by Bradley,[7] which provides a connection to the biomechanics of the foot swing. When these two methods are compared, two significant differences are observed: first, as already mentioned, there is no bulk velocity and second there is a backward drag when a person walks on the treadmill. Therefore, the velocity results shown in Bradley's model-based spectrogram is about 1.34 m/s more than the experimentally-extracted velocity of a walking human foot. The distal and proximal velocities are observed in both Bradley's model-based and our experimental approaches. The Doppler velocity bandwidth observed in our method and the one calculated in Bradley's method are almost same. The changes in the Doppler velocity bandwidth at 4.35 to 4.88 s shown in Fig. 1 compare well with Bradley's foot results shown in Fig. 3a of Ref. 7 and are understood as follows.

Referring to the time when the foot is on the treadmill and at the greatest distance from the sensor, the proximal end of the foot or heel initially lifted to rotate about the ankle and then the distal end of the foot or toe lifted off the treadmill (4.35–4.55 s). During this time period, the Doppler velocity had the largest bandwidth. As the foot swung forward, the distal and proximal foot ends became aligned with the transducer and the bandwidth first narrowed (4.55–4.65 s) and then broadened as the foot continued to rotate about the ankle causing the bandwidth to increase (4.65–4.75 s). As the foot approached contact the rotation reversed, the bandwidth narrowed and heel contact occurred (4.88 s). During the later time period, the velocity decreased more rapidly compared to the lift-off phase. This observed asymmetry indicates greater acceleration and therefore a larger force on the foot during heel strike compared to toe lift-off. The authors have used force plates[9] on treadmills to measure these forces and this same asymmetry was observed in these measurements. See, for example, Fig. 5 in Ref. 9.

The returns from the lower leg are shown in Fig. 2, and constitute the reflections from the proximal end of the foot and from the distal end of the thigh. The amplitude of these returns is stronger than the foot and is most pronounced when the lower leg was perpendicular to the treadmill surface, as can be seen in Fig. 2 from 6.1 to 6.5 s. This was due to the fact that the maximum cross section of the lower leg was exposed to the transducer. Similar to the foot spectrogram, the lower leg spectrogram also exhibits the backward drag on the treadmill from 6.3 to 6.7 s and at this time the leg was not swinging. The amplitude of the leg spectrogram is about −25 dB, and is more than the foot spectrogram because of its larger cross section. The maximum velocity of the lower leg was 3.45 m/s at 7.65 s, which occurred at its distal end. The velocity at the proximal end at 7.65 s was 0.[7] The area between the proximal end and the distal end is completely filled in and can be verified by Bradley's method. It is shown in Fig. 2 that the proximal end of the leg generated a very small velocity compared to its distal end, and therefore had a greater Doppler velocity bandwidth. The Doppler velocity bandwidth of the leg is greater than the velocity bandwidth of the foot because of its greater length.[7]

The third segment extracted experimentally was the upper leg or the thigh of a walking person on a treadmill. A plot of the Doppler velocity vs. time of the thigh is shown in Fig. 3, in which the maximum Doppler velocity observed at is 0.64 m/s at 5.35 s. The Doppler velocity of

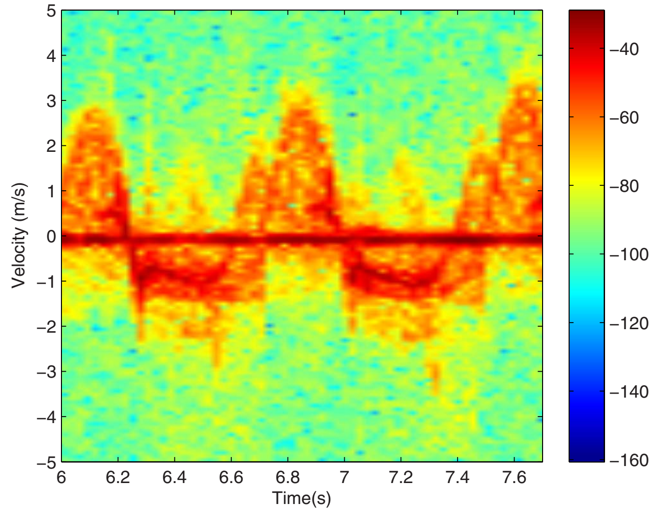

Fig. 2. (Color online) Leg spectrogram of a walking human on the treadmill.

the thigh was smaller, but its amplitude (5 dB) was greater than the foot and the lower leg. During human walking, the thigh spectrogram exhibited a smaller swing compared to both the foot and the lower leg, but stronger amplitude due to its larger cross-sectional area. Like the lower leg, the area between the proximal end and the distal end of the lower leg is also completely filled in. The Doppler velocity at the proximal end was almost zero because it occurs at the axis of rotation. The reflections from the right thigh exhibiting maximum velocity can also be observed at 5.75 s. The small screen used to block the right thigh does not work effectively when the right thigh moves backward. However, during right leg forward motion significant backscattering was blocked. This was because the gap between two thighs is smaller than gap between the legs or the feet and is harder to isolate acoustically.

Another human body segment that is a major contributor in human motion Doppler signature is the torso. The torso exhibits a unique Doppler signature that is almost sinusoidal. To acquire torso or chest data, we focused the UDS on the chest of a walking human on a treadmill.

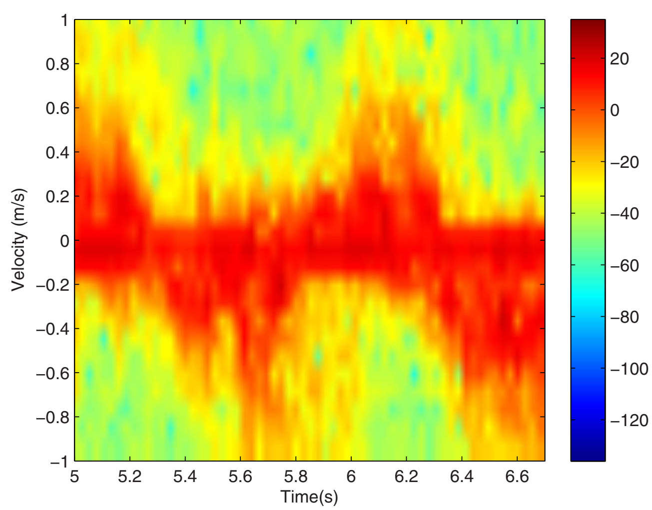

Fig. 3. (Color online) Thigh spectrogram of a walking human on the treadmill.

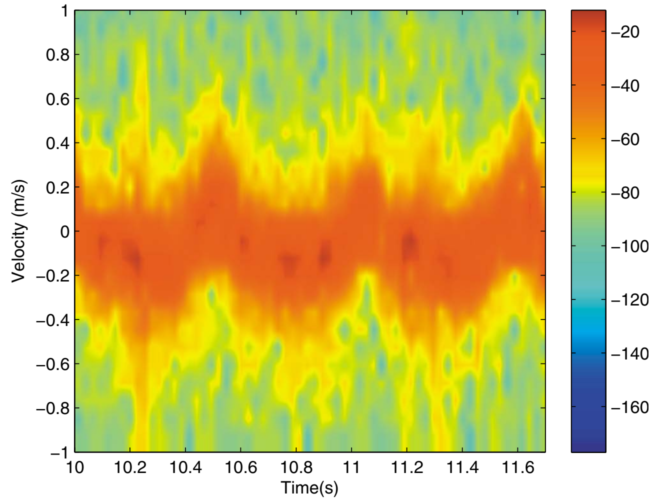

Fig. 4. (Color online) Chest spectrogram of a walking human on the treadmill.

The spectrogram of the chest velocity data is shown in Fig. 4. It is evident from Fig. 4 that the amplitude of the torso was strong due to its larger cross-sectional area. But the maximum Doppler velocity of the chest is about 0.5 m/s and is less when compared to the foot, lower leg, or the thigh. One of the distinct features of the chest spectrogram is the vibration frequency of the chest, which is twice that of any other body segments (foot, lower leg, etc.).[6] Torso results obtained were also verified with Bradley' method[7] and were found to be in agreement.

5. Conclusion

The Doppler signatures of different segments of human body such as foot, lower leg, thigh, and torso were extracted experimentally. The Doppler velocities of each of these segments were then computed from their Doppler signatures. The measurement were made using a 40 kHz UDS by illuminating one segment of a walking human body at a time while acoustically screening the other human body segments. The experimental results thus obtained were verified with Bradley's method. As only the foot, leg, and torso motions are the major features in whole human body motion, the experimental extraction of these features may be used as a basis to distinguish walking humans from walking quadrupeds. The method presented in this letter is an alternative to video analysis.

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